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The Creation of High Quality Positron Beams Using Traps

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Abstract. High quality positron beams are currently used for a variety of applications in science and technology. One of the most demanding applications is as analytical tools for surface and materials science, where ultra-short positron pulses (<200 ps) and microscopic beams (<1 micron in diameter) are desirable. Positron traps offer a qualitatively new method for beam formation and manipulation that has significant advantages in efficiency, flexibility, and cost over current beam conditioning techniques. One important capability is brightness enhancement by radial compression of the positron plasma using the rotating wall technique developed for electron and ion plasmas. A second capability is the production of ultra-short positron pulses required for positron annihilation lifetime spectroscopy. This can be accomplished using a trap by means of the simple technique of quadratic potential bunching, thus avoiding multiple stages of rf bunching currently used to produce pulsed positron beams.

INTRODUCTION

Over the past 30 years low-energy positron beams have been developed for a variety of scientific and technological applications. These include fundamental studies of atomic physics phenomena [1], mass spectrometry [2], and the analysis of surfaces and solids [3,4]. During this period, positron beam fluxes have increased by at least six orders of magnitude, while techniques have been developed for producing pulse widths of less than 100 ps and beams with diameters of less than 1 μm. Many of the developments in positron beam conditioning have been adapted from electron beam technology, and the limits of these techniques have now been reached. Further advances must therefore involve the development of stronger positron sources or must appeal to different approaches.

One of the most promising new approaches to the creation of high quality positron beams is the use of positron traps. These devices have been extensively employed for studies of positron-molecule interactions [5,6], mass spectrometry [2], electron-positron plasma experiments [7], and astrophysical simulations [8]. They have also been applied to a limited extent for beam condition on LINACS [9]. More recently a positron trap was used to create an ultracold positron beam [10] and this beam has been used for ground breaking studies of positron-molecule interactions in a previously inaccessible low-energy regime [11,12].

However, these experiments have exploited only a fraction of the potential capabilities for beam conditioning using traps. In this paper, we present some of these capabilities, including the potential for producing ultrashort positron pulses and microbeams.

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POSITRON TRAPPING

Trap-based positron beams assume that the positrons have been accumulated in a Penning trap. A variety of techniques have been proposed or developed for trapping positrons, including trapping by collisions with a buffer gas [13], trapped ions [14] or trapped electrons [15], trapping by electronic damping [16], chaotic orbits and field ionization of Rydberg positronium atoms [17]. Of these, only the buffer gas technique has the efficiency to be usable for high throughput beam systems, although trapping using ions has the potential to achieve similar high efficiencies.

For the buffer-gas approach, the trap has three stages of successively lower pressure, established by differential pumping, and electrostatic potential. Radial confinement is by an axial magnetic field [18, 19]. Positrons from a conventional positron source are trapped by collisions with a buffer gas, usually nitrogen, in the high pressure region and accumulate and cool in the low pressure region. Trapping efficiencies of $> 30\%$ have been achieved, and up to 3×10^8 positrons have been accumulated in eight minutes from a 70-mCi 22Na source. This system is tolerant of low-quality positron beams of the type obtained from rare gas moderators, which makes it suitable for high flux systems.

POSITRON BEAM TECHNOLOGY

Positron Beam Applications

Positron beams have been widely exploited as diagnostics of surfaces and solids [3]. These techniques involve the injection of a positron beam onto a surface, and measuring the particles or photons that are emitted. A variety of properties can be measured, including the surface composition, crystal structure, and concentration and distribution of vacancy type defects. In some cases, positron beam techniques provide similar information to their electron-beam analogues. For example, Low-Energy Positron Diffraction (LEPD) is analogous to Low-Energy Electron Diffraction (LEED), and Positron Annihilation Induced Auger Electron Spectroscopy (PAES) is analogous to Electron Auger Spectroscopy (AES). In other cases, positron based techniques provide information not available using electron beams. In particular, techniques based on the annihilation and positronium formation channels, which are not available for electrons, can provide unique information. For example, Positron Annihilation Spectroscopy (PAS), which measures the Doppler broadening of the 511 keV annihilation line, and Positron Annihilation Lifetime Spectroscopy (PALS), which measures the lifetime of positrons in materials, provide the most sensitive measure available of the size distribution and concentration of vacancy type defects.

Furthermore, even in cases where the same information is available using electrons, the analogous positron technique often has significant advantages. For example, in contrast to AES, PAES is carried out using low energy positron beams and can provide spectra that are essentially free from background secondary electrons [20].

One of the most important areas of current research using PAS and PALS is the characterization of the low-*k* dielectrics that are being used to increase the clock speeds

of integrated circuits [21]. Using PAS it is possible to measure the dielectric constant of these films in a non-destructive way [22], thus providing a potential quality control tool for IC production lines. The techniques also provide sensitive measurements of crystal lattice damage from ion implantation. Another important area is the measurements of aging and other properties in polymers [23].

Positron Beam Requirements

Each positron-based technique has its own particular beam requirements. In general, maximum beam flux is desirable. For some applications such as time-of-flight PAES and PALS, ultrashort positron pulses (< 200 ps) are desirable. For atomic physics experiments, ultracold positron beams are useful. Many techniques benefit if they are implemented using scanning microbeams (< 1 μm in diameter) so that spatially resolved information can be obtained.

Current technology uses complex rf bunchers and choppers for producing short pulse beams, while the inefficient technique of remoderation brightness enhancement [24] is used to produce microbeams. As described below, positron traps can be used to perform both of these functions with the potential advantages of improved efficiency, simplicity and reduced cost.

Beam Bunching

A variety of techniques have been developed for producing pulsed positron beams. The most advanced of these have the capability for producing subnanosecond positron pulses. One of these techniques is the harmonic potential buncher developed by A. P. Mills [25]. This applies a harmonic potential over the flight path of the positrons, thus producing a spatio-temporal focusing effect at the point of lowest potential. This technique has been applied to beams in flight, but it can be implemented in a much simpler and more effective way using trapped positrons, because the effect is strongest when applied to a pulse of positrons that is much shorter than the flight path. This can be easily accomplished using trapped positrons, and moreover, the trapping electrode structure can be used to provide the harmonic potential.

Brightness Enhancement

Several positron applications require microbeams, which can be produced using traps by a combination of two techniques, namely plasma compression prior to beam extraction, and extraction of positrons from the center of the plasma.

The smallest diameter to which a positron beam can be focused is determined by the relation [26]:

$$d_{\min} \simeq \frac{\varepsilon}{\alpha\sqrt{E}}, \tag{1}$$

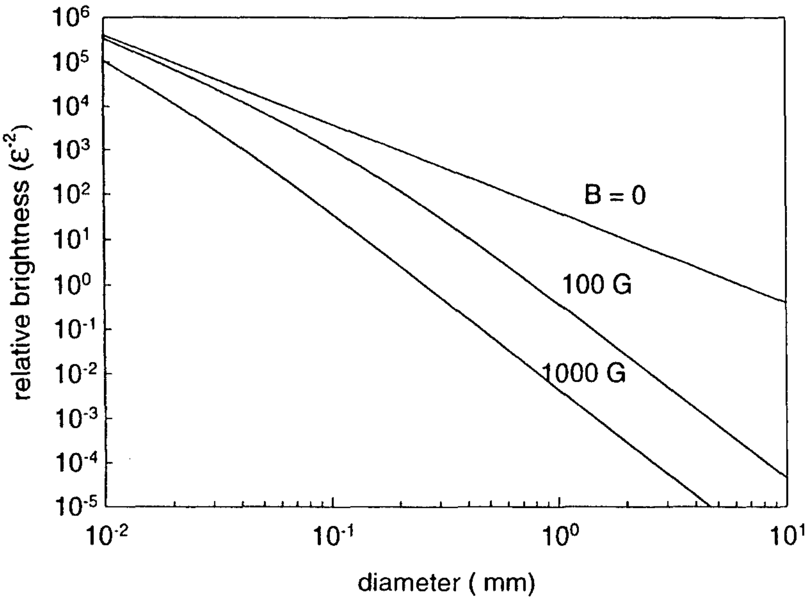

FIGURE 1. Relative brightness of a positron beam as a function of beam diameter for $E_\perp = 0.025$ eV.

where α and E are the convergence angle and energy of the beam at the focus and ε is the beam emittance. For a beam extracted from a magnetic field B, the emittance is given by [27]:

$$\varepsilon \simeq d\sqrt{\Delta E_\perp} + \frac{1}{2\sqrt{2}}\sqrt{\frac{e}{m}}d^2 B. \tag{2}$$

Figure 1 shows the dependence of the relative brightness, $1/\varepsilon^2$, on beam diameter for various values magnetic field strength. From this figure it can be seen that the magnetic field has the effect of reducing the brightness of the beam, but considerable brightness enhancement is possible by compressing the plasma radially. It also illustrates the importance of working at as low a magnetic field as possible.

Plasma compression is achieved by applying a rotating electric field to the plasma [28]. This is accomplished by applying suitably phased sine waves to azimuthally segmented confining electrodes. Figure 2 shows the development of radial distribution of a positron plasma in time during the application of a rotating electric field [29, 30]. These data were obtained in a relatively low magnetic field using a buffer gas to cool the plasma during compression. This proof-of-principle experiment demonstrated that significant radial compression ($\sim$20 increase in central density) and rapid compression ($d\dot{N}/dN \sim 15$ sec^{-1}) could be obtained in a good vacuum environment ($p \sim 10^{-8}$ torr) where the annihilation is negligible ($\tau_a > 1000$ s). As described below, this technique is being refined and implemented in an advanced trap-based positron beam system.

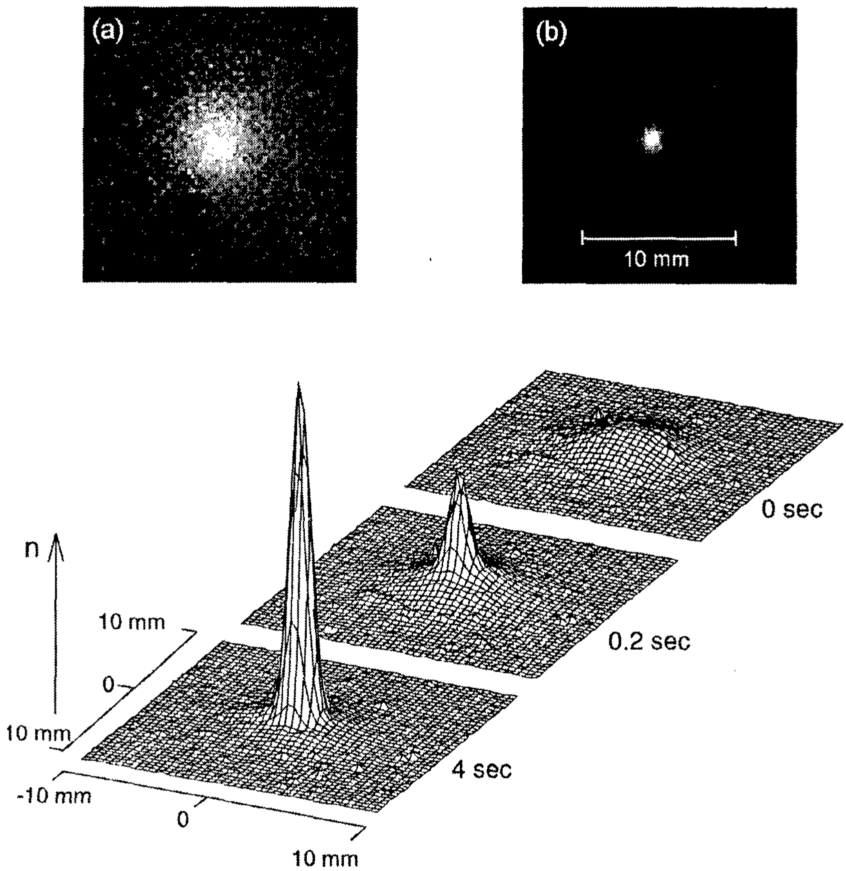

FIGURE 2. (a) and (b): CCD images of positron plasmas at $t = 0$ and $t = 4$ s respectively. (c) Radial profiles of a positron plasma with $N_{tot} = 10^7$ positrons, $f_w = 2.5$ MHz, $A_w = 56$ mV, and 2×10^{-8} torr of CF_4.

ADVANCED TRAP-BASED POSITRON BEAM SYSTEMS

First Point Scientific, Inc. (FPSI) is currently developing an Advanced Positron Beam Source (APBS) based on a two-stage buffer gas trap. This system features a compact, low-cost design and the capability for producing subnanosecond positron pulses using a harmonic potential buncher. FPSI is also developing a separate, differentially-pumped third stage, the Positron Trap Beam Source (PTBS), featuring a rotating electric field and advanced extraction system for producing microbeams. The layout of these systems is shown in Fig. 3.

Features of the systems include the capability of producing pulse widths of < 200 ps (for a stand alone APBS system), and ultracold (< 8 meV energy spread), small diameter (~ 10 μm) beams for the APBS/PTBS system in the magnetic field. After extraction from the field and focusing, it is expected that microbeams can be obtained by focusing.

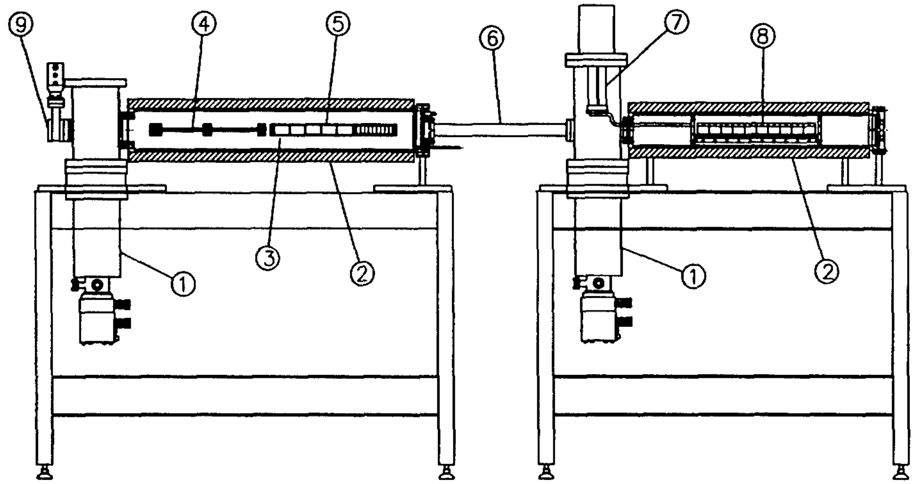

FIGURE 3. Layout of the APBS (left) and the PTBS (right) showing: 1. Cryopumps; 2. Solenoid magnets; 3. Confining electrodes; 4. High pressure section; 5. Intermediate pressure section; 6. Differential pumping section; 7. Cold head; 8. Confining electrodes in lower pressure region including rotating wall section; and 9. Entry port for positron beam.

Throughput is expected to be 30–40% of the incident beam.

These systems are expected to form the basis of a new generation of trap-based positron beam systems with advantages of lower cost, greater compactness and improved performance over existing systems.

CONCLUSION

A new generation of positron beam systems is being developed based on positron trapping techniques. These systems will have unique capabilities for producing bright, ultracold, pulsed positron beams with a variety of applications in scientific research and in industry.

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